

Detecting dark photon dark matter with Gaia-like astrometry observations

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Abstract. A class of dark photon dark matter models with ultralight masses would lead to oscillation of a test body through a coupling with baryons or $B - L$ charge. This periodical oscillation of an observer results in swing of a star's apparent position due to the effect of aberration of light, which could be probed with high-precision astrometry observations of stars in the Milky Way. We propose to use the observations of stellar positions of a number of stars by *Gaia* to search for this kind of dark photon dark matter. We show that this astrometry method is able to give promising sensitivities to search for the dark photon dark matter in the mass range of $10^{-23} \sim 10^{-21}$ eV.

Keywords: cosmology of theories beyond the SM, dark matter experiments, particle physics
- cosmology connection, stars

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Contents

1	Introduction	1
2	Effect on stellar location due to DPDM	2
3	Sensitivity of DPDM searches with Gaia	3
4	Conclusion	6

1 Introduction

About 24% of the energy density in our current Universe is composed by dark matter (DM). However, the identity of DM remains a big mystery. Very interestingly, the DM particle can be a boson with ultralight mass. If its mass is around 10^{-22} eV, its de Broglie wavelength in a dwarf galaxy is comparable to the core size of the galaxy. Such a DM candidate may provide a viable solution to the core-cusp problem in low-mass galaxies [1–4].

One natural candidate for the ultralight DM particle is dark photon (DP), whose mass is protected by a gauge symmetry. The mass regime we are interested in here is extremely small, $O(10^{-22})$ eV, and the local occupation number for the dark photon DM (DPDM) is very large. In such a case, the DPDM could be treated as a background oscillating field instead of individual particles.

Since we consider the scenario in which the DP mass is much smaller than keV, the DPDM cannot be produced thermally. One typical way for the non-thermal production of the DPDM is through the misalignment mechanism, where the DM relic abundance is induced by a non-trivial initial condition of the dark photon field [5]. More details and subtleties about the DPDM are further explored in [6, 7]. Additionally, several other production mechanisms are studied recently, such as the DPDM production through the parametric resonance, the tachyonic instability or a network of cosmic strings [8–12].

There have been many novel proposals to look for the DPDM in the light or ultralight mass regime. For example, the resonance conversion in a cavity, LC-circuit or dish antennas are studied in [13–17]. The DPDM can also be absorbed by careful choices of target materials which consequently causes observable excitations [18–25]. Rather than building new experiments to look for DPDM, its existence can also be checked in many existing experiments, which are built for totally different scientific purposes [26–29].

In this paper, we focus on the scenario that the dark photon is the gauge boson of $U(1)_B$ or $U(1)_{B-L}$.¹ In this case, any object that carries B or $(B - L)$ number, will experience a force caused by the DPDM background. This force leads to oscillations of the object, which could be consequently detected. For the very low mass range of the DPDM, the oscillation period is about years, which is reachable by the pulsar timing array or astrometry method.

Here we propose to use very high-precision measurements of stellar locations and movements by Gaia satellite to probe the oscillation effect induced by the ultralight DPDM. Gaia

¹Note that $U(1)_B$ is anomalous under the standard model gauge group. However, such anomaly, with the DP being massive, can be canceled by the Green-Schwarz anomaly cancellation mechanism.

is an astrometry mission of the European Space Agency (ESA), launched in 2013 and expected to operate until 2022 [30]. The positions, parallaxes, and annual proper motions of more than one billion stars with unprecedented precision will be obtained by *Gaia*, which are expected to be revolutionary in understanding the structure and dynamics of the Milky Way, the stellar physics, exoplanets, and even the fundamental particle physics. The location accuracy of *Gaia* depends on the brightness of the target star, and is in general about tens of micro-arcseconds for stars brighter than 15 mag [30]. Such an accuracy is found to be useful in probing very tiny apparent motions of stars caused by e.g., gravitational waves from inspirals of binary super-massive black holes [31].

2 Effect on stellar location due to DPDM

Let us first properly model the DPDM background. The DP is a massive vector boson. There are 4 components of the DPDM field, A_μ , but only three of them are independent. We choose to use Lorentz gauge, i.e. $\partial^\mu A_\mu = 0$, in our discussion. In the non-relativistic limit, the Lorentz gauge implies that A_t has a much smaller oscillation amplitude compared with spatial components \mathbf{A} . In addition, the contribution from A_t component to the dark electric field is further suppressed by DM velocity, thus we will only focus on \mathbf{A} in later discussions.

Within a coherence length, $l = 2\pi/(m_A v_0)$, the DPDM field can be approximately written as $\mathbf{A}(t, \mathbf{x}) = \mathbf{A}_0 \sin(m_A t - \mathbf{k} \cdot \mathbf{x})$. Here we set the initial phase as zero without losing generality. We also ignore the kinetic energy contribution to the oscillation frequency. Typically, for $v_0 \sim 10^{-3}$, we have $l \sim 0.4(m_A/10^{-22} \text{ eV})^{-1} \text{ kpc}$. As mentioned before, we focus on the scenario where the DP is the gauge boson of gauged $U(1)_B$ or $U(1)_{B-L}$ group. It couples with the baryon or baryon-lepton charge of the test body. Analogue to a charged particle posed in an ordinary electromagnetic field, an acceleration is induced to a test mass when it carries $U(1)_B$ or $U(1)_{B-L}$ number and is embedded in the DPDM background. The acceleration can be approximately calculated as [28]

$$\mathbf{a}(t, \mathbf{x}) \simeq \epsilon e \frac{q}{m} m_A \mathbf{A}_0 \cos(m_A t - \mathbf{k} \cdot \mathbf{x}), \quad (2.1)$$

Here ϵ characterizes the coupling strength of the DP. It is normalized in terms of the electromagnetic coupling constant e . Further q and m are the dark charge and the mass of the test body. In our study, the “charge” q equals to the total number of baryons or neutrons for an electric neutral object.

One can also consider the scenario where dark photon couples to SM particles through kinetic mixing with the ordinary photon. In this case q is simply the electric charge that the test body carries [32]. However the screening effect induced by the interstellar plasma can induce a large suppression in the parameter space that we can probe. Thus we will not consider this scenario in this study.²

The velocity variation due to the acceleration given in eq. (2.1) is

$$\Delta \mathbf{v}(t, \mathbf{x}) \simeq \epsilon e \frac{q}{m} \mathbf{A}_0 \sin(m_A t - \mathbf{k} \cdot \mathbf{x}). \quad (2.2)$$

²For ordinary electromagnetic field, the interstellar plasma has cutoff frequency as $\omega_{pe} = \sqrt{4\pi e^2 n_e / m_e} \sim 5.7 \times 10^4 (n_e / \text{cm}^{-3})^{1/2} \text{ Hz}$. For the DPDM, the cutoff frequency is expected to be smaller by a factor of ϵ . To see how important the screening effect can be, we first neglect the screening effect and estimate the sensitivity on ϵ that can be achieved by the method proposed in this paper. We find that the value of ϵ that can be probed is too large and the screening effects cannot be consistently ignored. Thus we will leave the discussion of this scenario for future studies.

Such a periodic velocity variation would lead to a slight swing of a star's apparent location, which is known as the aberration of light due to a moving observer. For a star with original direction \mathbf{n} (defined as a unit vector pointing from the satellite to the star assuming no effect from the DPDM coupling), its apparent angular deflection due to the velocity change $\Delta\mathbf{v}$ should be ($c = 1$)

$$\Delta\theta \simeq -\Delta v \sin\theta, \quad (2.3)$$

where $\Delta v = |\Delta\mathbf{v}|$ and $\cos\theta = \Delta\mathbf{v} \cdot \mathbf{n} / \Delta v$.

The DPDM coupling will also lead to oscillations of distant stars (known as the star term). The estimated angular oscillation of the star term is $\Delta\theta_s < \Delta v \cdot t/d \ll \Delta\theta$, where $t \sim 1$ year is the observational time and $d \sim 1$ kpc is the typical distance of a star.³ Only for stars which are very close to the Earth, e.g., $d < 1$ pc, the star term becomes comparable to the detector-induced term eq. (2.3). Therefore we can neglect such oscillation effects of stars themselves.

The frequency range that **Gaia** sensitive to is about $10^{-8} \sim 10^{-6}$ Hz, which corresponds to a mass range of the DPDM of $4 \times 10^{-23} \sim 4 \times 10^{-21}$ eV. For a frequency lower than 10^{-8} Hz, the apparent angular deflection varies quite slowly with time. This is similar to the proper motion of a star and will be largely removed when one subtracts the proper motion [31]. For a higher frequency, the observational cadence needs to be very high to have effective sampling of the angular deflection due to the DPDM. These effects will explain the behavior in the sensitivity estimation which will be presented in the next section.

3 Sensitivity of DPDM searches with Gaia

To perform a solid estimation on the sensitivity that can be achieved by our proposed analysis using **Gaia**-like astrometry observations, we simulate stellar motions with and without the DPDM coupling. Following ref. [31], we assume that the orbital motion of the satellite surrounding the Earth and Sun can be precisely corrected, leaving only the stellar proper motion and the DPDM coupling effects to be considered here. This is reasonable for **Gaia** which employs a series of orbit control and reconstruction techniques to ensure an accuracy of tens of μas of the stellar location measurement [30].

We use a quadratic model to approximately describe the proper motion of a star. For each star, its initial velocity and acceleration are randomly assigned, assuming Gaussian distributions with mean values as zero and standard deviations as 50 km s^{-1} and $20 \text{ km s}^{-1} \text{ yr}^{-1}$, for the right ascension and declination directions. The proper motion can be subtracted through a fit to multiple measurements, $\sim O(100)$, within the lifetime of the mission [31].

The angular deflection induced by the DPDM is further added on top of the proper motion. The direction of the gauge field \mathbf{A} is described by an equatorial coordinate (α, δ) which are free parameters to be inferred from the data. From eq. (2.2), DPDM induced change in velocity is written as

$$\Delta\mathbf{v}(t, \mathbf{x}) \simeq \epsilon e \frac{q}{m} A_0 \mathbf{n}_0 \sin[m_A(t - t_0) + \phi], \quad (3.1)$$

where $\mathbf{n}_0 = (\cos\delta \cos\alpha, \cos\delta \sin\alpha, \sin\delta)$, t_0 is the zero point of the simulated observation. Here we do not include the phase change caused by $\mathbf{k} \cdot \mathbf{x}$, which is safely negligible in the parameter region we are interested in. For example, the coherence length for the parameter

³Note that we do not require the stars and the detector to be within one coherence length of the DPDM field.

space we are interested in is about $0.01 \sim 1$ kpc given the velocity $v_0 \sim 10^{-3}$. The largest motion of the satellite in the Milky Way is about 3×10^{-4} pc yr $^{-1}$, assuming again a velocity of $\sim 10^{-3}$ of the Sun. The movement distance of the detector is thus significantly smaller than the coherence length of the DPDM, and it is safe to treat the DPDM field as spatially universal in the local environment.

We randomly generate 10^4 stars uniformly distributed in the sky.⁴ For each star, 75 observations are performed within 5 years with a uniform cadence, which is comparable to the average design performance of *Gaia* at the end of mission [30]. The localization accuracy of the *Gaia* satellite is assumed to be $100 \mu\text{as}$. Note that in reality such an accuracy depends on the magnitude of a star [30]. This subtlety is not included in the current study. We adopt the data compression technique proposed in ref. [31], which gives a significantly improved location accuracy by measurements of a large number of stars in a small sky cell. Here we assume a compression ratio of $10^9/10^4 = 10^5$, which gives a noise level of $\sigma = 100 \mu\text{as}/\sqrt{10^5}$. In our study, for each observation of a star, a Gaussian noise with σ is added when we simulate the positions of stars. The proper motion parameters (in total 4 parameters describing the velocity and acceleration in two orthogonal directions) are derived through fitting the 75 observations of each star with the quadratic model. At last, we subtract the proper motion with the best-fit parameters in order to study the remaining motion of stars.

As an illustration, we assume that the dark photon is the gauge boson of $U(1)_B$, and we take the input parameters as $(m_A, \epsilon, \phi, \alpha, \delta) = (10^{-22} \text{ eV}, 3 \times 10^{-24}, 2.59, 1.25, 0.68)$. Except for the mass and the coupling constant, the other parameters are randomly generated. We employ the Markov Chain Monte Carlo (MCMC) method [33] to fit the model parameters from the mock data. We find that the model with the DPDM interaction gives significantly better fit to the simulation data. Compared with the **null** hypothesis without the DPDM interaction, the χ^2 value of the model with the DPDM interaction is smaller by about 70. The fitting distributions of the model parameters are shown in figure 1, from which we can see that the input parameters are reasonably reproduced.

To estimate the sensitivity of detecting the DPDM that the astrometry observations can reach, we vary the coupling constant ϵ for different choices of m_A , and repeat the above simulation and analysis. The 95% confidence level of a detection is defined as that the difference of the χ^2 between the **signal** hypothesis and the **null** hypothesis is about 9.7, with four additional degrees of freedom in the **signal** hypothesis.

The derived sensitivities of the coupling constant ϵ^2 as functions of the DPDM mass are shown in figure 2, for the $U(1)_B$ (top) and $U(1)_{B-L}$ (bottom) types of coupling. Note that the sensitivities are presented by a band which is the envelope of the results considering fluctuations due to different realizations of the sample and the random choices of the initial phase.

We note that if m_A is smaller than $10^{-22.5}$ eV, the oscillation frequency becomes very small, and the signal starts to degenerate with the proper motion for a limited observation time (a few years). In this case the sensitivities become weaker. Also we can see that the sensitivity band becomes wider when m_A is smaller. This is because in the low frequency region, the signal degenerates with the background to different extent for different initial phase of the DPDM field, and the background subtraction gives different results.

⁴This is a zeroth-order approximation. Considering a more realistic distribution of stars with a concentration along the Galactic disk will result in a non-uniform sensitivity for the DPDM field with different orientation. Including this subtlety does not change our qualitative conclusion.

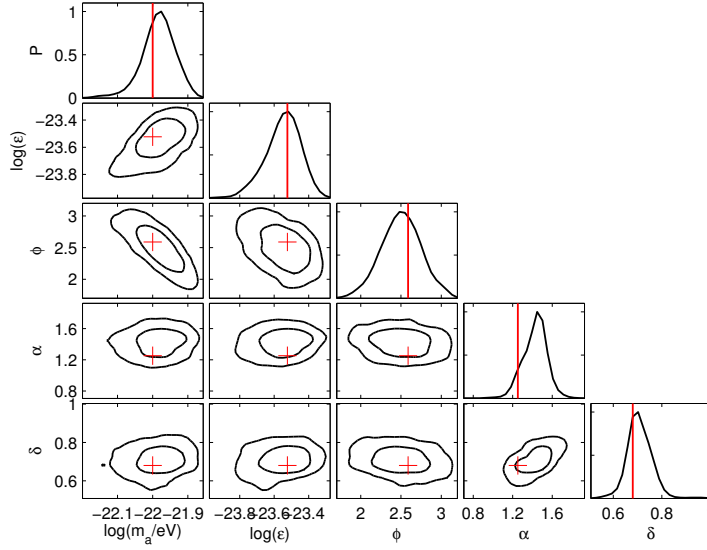


Figure 1. Fitting 1-dimensional probability distributions (diagonal) and 2-dimensional credible regions (off-diagonal; 68% and 95% credible levels from inside to outside) of the model parameters based on simulated astrometry data of 10^4 stars. The red lines and crosses show the input parameters of the simulation.

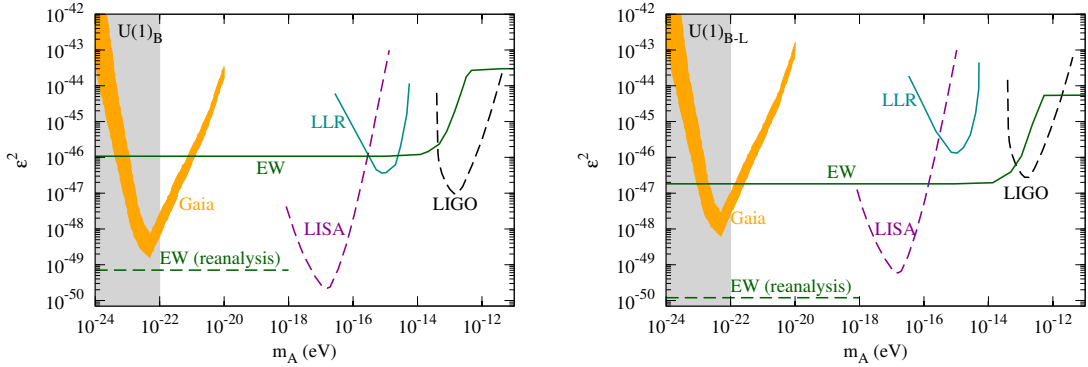


Figure 2. Expected 2σ exclusion limits of the DPDM coupling constant from 5-year astrometry observations of **Gaia** (orange bands), for the $U(1)_B$ (left) and $U(1)_{B-L}$ (right) types of coupling, compared with those from the EW experiments [26, 34, 35], the LLR experiment [36–38], and the expected sensitivities of gravitational wave experiments LISA and LIGO [28]. The grey shaded region marks out the parameter region with $m_A < 10^{-22}$ eV, in which the de Broglie wavelength of the DPDM is larger than the typical size of a dwarf galaxy [1].

For comparison, the experimental limits from the Eot-Wash (EW) experiments [26, 34, 35] and the Lunar Laser Ranging (LLR) experiment [36–38], and the expected sensitivities from the gravitational wave experiments LISA and LIGO [28] are also shown. In ref. [26] a re-scaling of the EW experiment result of [35] was performed to convert the static force signal induced by the Earth to the DM-induced signal, which is labelled as “EW (reanalysis)”. However, a dedicated reanalysis may be necessary to give actual bounds on

the parameter space. The astrometry method proposed in this work shows promising sensitivities for the DPDM mass range of $m_A \lesssim 10^{-21}$ eV, corresponding to frequencies smaller than 10^{-7} Hz.

4 Conclusion

In this work we propose to use the high-precision astrometry measurements, i.e. *Gaia*-like satellite, to search for the ultralight DM candidate. We consider the scenario where DM is composed by dark photon, which is the gauge boson of $U(1)_B$ or $U(1)_{B-L}$. In such scenario, the existence of DPDM is expected to lead a periodic oscillation of the satellite. This results in angular deflections of target stars due to the aberration effect. Benefiting from precise location measurements of a large number of stars, even a very weak DPDM coupling can potentially be revealed by extracting a universal oscillation pattern of all stars. We find that this proposed search strategy can probe a large unexplored parameter space of DPDM, e.g. a coupling as small as $\epsilon \sim 10^{-24}$ in the mass range of $10^{-23} \sim 10^{-21}$ eV.

There are other kinds of oscillation effects induced by various types of ultralight DM candidates, e.g., the axion, can also be probed with the astrometry method. The method studied in the paper serves an important complement in probing a class of ultralight DM models, which is proposed to be detected by the pulsar timing array [39–41].

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